Polar/TIDE Results on Polar Ion Outflows

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The ISTP Polar spacecraft is equipped with a unique plasma velocity analyzer system designed specifically for kinetic diagnostics of low-energy, low-density plasma ions. Such plasmas were previously unobservable in the polar cap region owing to their low velocities and the positive photoelectric charging of spacecraft in sunlight at low ambient plasma density. The thermal ion dynamics experiment (TIDE) incorporates seven large apertures, focusing electrostatic optics, and time-of-flight mass analysis, for enhanced sensitivity to low energy plasma ions. The plasma source instrument (PSI) limits and regulates the photoelectric charging of the Polar spacecraft at small potentials (~+2V). Together, TIDE and PSI have produced new observations of i) the mixing of solar and ionospheric plasmas in the cleft regions; ii) auroral heating and plasma transport; iii) solar illumination control of the polar cap ionosphere; iv) the downward motion of O^+ at lower altitudes throughout the polar cap region; v) the high altitude polar wind; vi) the high altitude convection of the polar outflows; vii) the unexpected dynamism of polar wind outflows; and viii) the supply of plasma to the plasma sheet. These observations indicate that most polar cap O^+ out flow originates in the dayside plasma upwelling region, creating a plasma fountain effect in the polar cap. The observations support the evaluation of consequences of the ionospheric source of plasma for magnetospheric dynamics and storm phenomena. Preliminary global modeling results indicate that ionospheric plasma is the dominant contributor to both the density and pressure of the plasma within a corresponding geopause that extends to the persistent neutral line in the central plasma sheet. TIDE and PSI have contributed fundamentally to our knowledge that the dissipation of solar wind energy is not limited to the ionosphere proper, but is distributed throughout a much larger geosphere of dominantly terrestrial origin.

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BACKGROUND

The earliest suggestions that terrestrial plasma escapes our planet supersonically were based upon theoretical considerations involving analogies with the solar wind [*Axford*, 1968; *Banks and Holzer,* 1968]. Based on the likely vacuum conditions in the wake of the Earth's magnetosphere, a polar wind of light ions was predicted to have supersonic outflow velocity when compared with very low thermal speeds characteristic of ionospheric plasma. Since then, polar wind outflows have been observed to begin in the topside ionosphere and to continue up to about 3.5 R_E altitude [*Ganguli*, 1996]. The significance of polar wind outflows was long thought to be limited to a high speed, low density phase of plasmaspheric refilling at high latitudes. Polar wind was not thought until recently to contribute significantly to the plasma sheet. Rather, accelerated outflows of ions from the auroral zones, including significant if not dominant components of O^+ ions, were thought more likely to contribute to plasma sheet and storm time plasmas, in part because they have already attained keV energies as they leave the auroral acceleration regions.

More recently, low energy observations led to the conclusion that the largest local fluxes of outflowing ions (mostly O^+ for solar maximum conditions) escape from the dayside cleft regions (including the cusps). The largest fluxes of O^+ were also found to be flowing at the lowest energies, less than 100 eV. In fact, the outflow was found to be a bulk phenomenon involving such strong heating that the core of the ion distribution exhibited temperatures of order 10 eV or higher at 1 R_E altitude. Test particle simulations of such outflows found that, owing to their starting positions on the dayside of the magnetosphere, such ions are able to travel long distances down the magnetotail. There, they are very strongly accelerated by their non-adiabatic interactions with the stretched and sharply curved magnetic field with associated convection electric field. Or, if they stray too far down tail, they may be lost entirely from the magnetospheric system. Those that are returned Earthward acquire plasma sheet-like energies, independent of how low their energies may have been upon arrival at the neutral sheet. H^+ ions also become plasma sheet-like upon interaction with the stretched neutral sheet.

Such considerations brought attention back to the polar wind outflows of light ions, extending over much of the high latitude ionosphere. These ions are flowing slowly, but fast enough to travel far enough down the tail to supply the plasma sheet with protons and helium ions in regions earthward of the most persistent neutral line, where the mantle plasmas are unlikely to be a strong source in the center of the plasma sheet ($Y_{GSM} \sim 0$). As these ions are accelerated to plasma sheet energies, they must be admitted and accounted for as a source of plasma in the plasma sheet.

TIDE and PSI [*Moore et al.*, 1995; *Moore et al.,* 1997] were conceived to provide competent plasma measurements as close as possible to zero energy, and consequently to reduce or eliminate spacecraft potential as a factor in observing low energy plasmas [*Comfort et al.*, 1998]. At the same time, the TIDE energy range was extended up to 450 eV, allowing for simultaneous direct observation of entering solar plasmas in the cusp/cleft regions, and of the auroral accelerated ion beams and conics at moderate energies. The results include a simultaneous look at mixed solar and ionospheric plasmas; a new perspective on auroral energized plasmas; a systematic sampling of the polar topside ionosphere at ~ 1 R_E altitude; and our first look at the high altitude behavior of the polar wind, which has been found to be much more dynamic and variable than expected. Altogether, a new data set has been collected that permits us to more comprehensively and quantitatively assess the transport of ionospheric plasma throughout the magnetosphere, and its relationship to solar plasma entry and transport processes.

CLEFT MIXING OF SOLAR AND IONOSPHERIC PLASMAS

Figure 1 shows an example of coexisting solar wind and plasmaspheric plasmas, observed in the dayside cusp region. Escaping plasmaspheric plasma was found to coexist with magnetosheath plasmas admitted inside the magnetosphere by reconnection in the high-latitude cusp region. Plasmaspheric material is accelerated significantly prior to observation at high latitude boundary layer locations, but is still distinct from the incoming magnetosheath plasma [*Dempsey et al.,* 1998; *Chandler et al.*, 1998; *Chandler et al.*, unpublished manuscript]. These observations of coexisting ionospheric and solar plasmas at the same location confirm what is qualitatively expected on plasma flux tubes connected to both plasma sources, given that reconnection creates such flux tubes, i.e. mixed components of solar and ionospheric plasmas [e.g. *Fuselier,* 1997]. The observations provide diagnostics on the connectivity of flux tubes and the location of reconnection sites along them. They also support comparison with a comprehensive quantitative theory of plasma transport in such plasma flux tubes (open to the magnetosheath), though such a theory has not yet been fully developed.

AURORAL PLASMA TRANSPORT

Plate 1 summarizes the observed characteristics of bulk transport of ionospheric plasma heated by auroral processes. The panels indicate the distribution of such events in location, flow velocity, temperature, and flux. Using the 0-450 eV energy range and 3D angular response of TIDE, ionospheric heating and outflow is well differentiated from magnetosheath plasma penetration into the dayside cusp ionosphere. Transverse ion heating and resultant outflow is found to be well-correlated in detail with UV auroral features. Ionospheric topside flows, conics and beams, are directly associated with auroral electric fields, plasma waves, and convection [*Hirahara et al.*, 1998a]. Event analysis of H^+ and O^+ conics in the polar cusp show angular and energy differentiation associated with a heating wall in the cusp [*Knudsen et al.* 1994; *Hirahara et al.*, 1998b]. The dayside upwelling ion region is active during these solar minimum conditions, producing strong upwelling fluxes of all species of ions, though not as enriched in heavy species as at solar maximum.

Auroral plasma density cavities observed at POLAR perigee (~1 R_E altitude) were also found to contain transversely heated and accelerated populations of ions. In cases where the spacecraft potential rose as high as ~+10V, a density drop as large as one to two orders of magnitude was found, relative to adjacent regions. In such events, the O^+ ions exhibit both conics and parallel flows [*Craven et al.,* 1998] having characteristic energies comparable to the spacecraft potential. This suggests that the density cavity results essentially from bulk energization of the ionospheric plasma. The plasma ions remain observable at auroral altitudes, with charging to levels not much greater than the typical ion energies.

CLEFT ORIGIN OF POLAR CAP O^+

Figure 3 illustrates the influence of solar illumination in control of polar wind H^+ fluxes and O^+ densities. Polar wind H^+ fluxes and O^+ densities at 5000km altitude are strongly correlated with increasing solar zenith angle (or day-night distance across the polar cap, in solar magnetic coordinates, X_{GSM}). This documents a strong solar illumination control of the plasma density, and thus the supply of both O^+ ions, and probably through charge exchange, H^+ ions as well [*Su et al.*, 1998a]. At this altitude in the polar cap, The O^+ plasma is a cold rammed distribution, while the H^+ and He^+ are in relatively well-developed outflow (though still transonic).

Figure 4 shows observations of topside O^+/H^+ plasma flow, showing that O^+ is on average downward moving in the polar cap. In contrast with the upwelling ion flows of all species in the dayside auroral zone, the polar cap O^+ plasma at perigee altitudes is on average a steady downward flow (with at most sporadic and localized upward flows). This shows unambiguously that the O^+ component of the polar cap plasma originates in the dayside upwelling region and does not flow up from the polar cap proper [*Su et al.*, 1998a]. It can be inferred from this that polar cap plasma tubes contain on average an oversupply of O^+ plasma relative to their low altitude boundary conditions, and yield O^+ back to the ionosphere even as they supply H^+ plasma outflows. Several recent theoretical studies have suggested that O^+ outflows can be expected from the polar cap if photoelectron effects are properly taken into account [*Ganguli*, 1996]. The present results suggest instead that photoelectron effects have not been properly accounted for if they produce significant polar cap O^+ outflows. To date, few theoretical efforts have incorporated convecting flux tubes that are subjected to strong heating as they pass through the auroral zone. The downward motion that results when the heat source is removed in the polar cap may overcome photoelectron effects that would otherwise produce upflows.

HIGH ALTITUDE POLAR WIND

Figure 5 illustrates the observed characteristics of the high altitude polar wind. The polar wind has been confirmed to exist at very high altitudes for the first time by the TIDE-PSI system [*Moore et al.*, 1997]. The escaping polar wind is faster, much hotter, and richer in O^+, compared with the polar wind predicted by thermal outflow theories. It is every bit as pervasive in the polar cap as expected from these theories [*Su et al.*, 1998a]. The real polar wind likely differs from that which has been described by theory primarily as a result of significant energy inputs in the topside auroral ionosphere. As plasma flux tubes convect through and interact with auroral zone processes (that is, magnetospheric boundary layer or plasma sheet processes), these energy inputs increase the escaping mass flux primarily through low altitude heating, but with contributions from the production of ionization and topside electron heating by soft electron precipitation.

MAGNETOSPHERE-IONOSPHERE COUPLING

Figure 6 shows observations of plasma convection in the high altitude polar wind, showing anti-sunward convection during a period of generally southward interplanetary magnetic field (IMF) and vice versa for a period of northward IMF. In conjunction with the Plasma Source Instrument (PSI), TIDE has the unique ability to simultaneously measure both convection velocities and parallel flows in the polar cap at apogee (8-9 R_E). The convection of polar wind outflows in the polar cap was found to respond to interplanetary conditions in accordance with expectations of a four-cell convection pattern with sunward convection in the polar cap for northward IMF. Thus, the polar wind outflows are strongly influenced by the solar wind interaction at the boundaries of the magnetosphere. In particular, high latitude reconnection has the effect of reversing high latitude boundary layer flows. This effectively shuts down the internal supply of plasma to the plasma sheet (at least in the local hemisphere), and tends to allow the low latitude boundary layer to dominate the anti-sunward transport of boundary layer plasma, feeding the plasma sheet.

POLAR WIND DYNAMISM

Plate 2 illustrates the degree of dynamism that is often observed in the high altitude polar wind outflows. With the accumulation of additional polar cap passes with PSI operating, we have noticed that the polar wind is quite often very strongly dynamic in outflow velocity. Fluctuations of the outflow velocity by a factor of 3 or more are typical in some regions, while other regions are characterized by relatively steady polar wind. The spatial/temporal scale of these fluctuations is such that many of them are observed in the course of a single pass through the polar cap (few hours). Such fluctuations are significant in controlling the fate of the outflows insofar as they may be lost downstream beyond the persistent neutral line at high velocities, captured and strongly accelerated in the plasma sheet if they are somewhat slower, or recirculated directly into the plasmasphere if they are very slow.

Often the fluctuations do not occupy the entire polar cap but are somewhat stronger near dawn or dusk. Correlated (or anti-correlated) fluctuations often occur in the simultaneously observed polar rain electrons (E~100eV) [*Su et al.*, 1998b]. The fluctuations are not accompanied by obvious correlated changes in the differential flux or apparent composition of the plasma (ratio of H^+ and O^+ differential fluxes), and it is believed that these represent the result of high altitude energy inputs in to the flow. One model that has been proposed for such fluctuations involves the existence of a standing electrostatic shock in the flow that confines the atmospheric photoelectrons while accelerating ions outward as they fall through the shock [*Su et al.*, 1998a]. Under some conditions, it has been suggested by *Barakat et al.*[1997] that the shock may fluctuate in altitude and/or amplitude, leading to the observed fluctuations in velocity at a slowly moving observing point. Fluctuations of such large amplitude had not previously been anticipated in polar wind outflows, and have an influence on the fraction of the polar wind that is lost from the magnetosphere down the tail.

PLASMA SHEET SUPPLY

Figure 8 summarizes a categorization of the types of trajectories resulting from initial conditions within the range of typical polar wind velocities and locations of observation for the TIDE-PSI data set. The convection, field aligned velocity, and location of the polar wind are all important factors in the ultimate destiny of the flow and resultant role that it will play in global magnetospheric dynamics. Single particle simulations in realistic fields [*Giles et al.*, 1997] provide the means to evaluate polar wind significance and destiny. Flows with a very high ratio of parallel to tailward cross-field flow (or even sunward flow, as described above) tend to be lost entirely from the magnetosphere through the tail lobes. Flows that are slow relative to their tailward convection tend to be recirculated within the inner magnetosphere supplying relatively cold plasma only to the plasmasphere. Flows like those observed from POLAR tend to enter the active parts of the plasma sheet, for typical convection conditions. Assuming their inertia does not load down the drivers of plasma sheet convection, H^+ ions in these outflows are energized instantly and unanimously on crossing the neutral sheet to plasma sheet, to energies of several keV, thus qualifying them immediately as a part of the plasma sheet ion population.

The omnipresence of polar wind outflow throughout the entire polar cap implies that some plasma will be provided to the active parts of the plasma sheet, almost independent of magnetospheric convection. For rapid polar cap convection, the denser, hotter and faster outflows of the dayside magnetosphere will be fed to the active plasma sheet regions inside of 30 R_E. For slower convection, the relatively low density outflows of the night side polar cap and the even lower density but energized outflows of the night side auroral zone will be fed to the active plasma sheet. For very slow or even reversed polar cap convection, polar outflows will be largely lost through the lobes or into the low latitude boundary layer and magnetosheath.

These results, combined with the observed cold, dense character of the plasma sheet for northward IMF [*Terasawa et al.*, 1997], suggest a paradoxical inference. It would seem that the hot low density plasma sheet during active convection conditions is actually supplied by the ionospheric polar outflows, while the cold dense plasma sheet found for northward IMF is supplied from the magnetospheric flanks by residual low latitude boundary layer circulation.

SUMMARY AND PLANS

The following noteworthy scientific accomplishments resulted from the main mission phase of TIDE-PSI data acquisition:

1. Plasmaspheric plasma outflows were found to coexist with magnetosheath plasmas in the cusp/cleft region, on reconnected field lines;
2. Transverse ion heating and resultant outflow was found to be correlated in detail with UV auroral features and associated electric fields and waves; Auroral plasma density cavities observed at POLAR perigee (~1 R_E altitude) were found to contain transversely heated and accelerated populations of ions with characteristic energy comparable to the s/c potential;
3. The polar wind H^+ flux and O^+ density near 1 R_E were found to be strongly controlled by solar illumination;
4. The O^+ component of the polar plasma was shown to originate mainly in the dayside cleft region rather than in the polar cap proper;
5. The 6-9 R_E altitude polar wind, observed for the first time, was found to be faster, hotter, deficient in He^+ and richer in O^+ content than in thermal outflow theories, consistent with signficant contributions from dayside plasma heating processes;
6. Convection of polar wind outflows in the polar cap was found to respond to interplanetary conditions in accordance with the creation of a sunward plasma flow

in the polar cap for Northward IMF B_Z, with clear implications for transport of plasma to the plasma sheet.

7. The high altitude polar wind was found often to be dynamic in space and/or time, with fluctuations in velocity having amplitude of a factor of order three;
8. Using 3D test particle simulations, the polar wind outflow was shown to supply plasma to active plasma sheet regions where neutral sheet acceleration immediately accelerates the protons to plasma sheet energies of several keV.

Future work on the Polar/TIDE data set will include continued acquisition, processing, correlative analysis, and interpretation of low-energy plasma data. The objectives of these studies for the Solar Maximum Initiative focus on the variations of low-energy plasma transport within the magnetosphere. We have learned that ionospheric plasma outflows are a pervasive feature of the low density polar cap and lobe regions, as well as the boundary layers and auroral zones. We now seek to 1) document and understand the dependence of these outflows upon heliospheric conditions as solar activity increases through solar maximum, and 2) understand the influence of solar-dependent plasma flows upon the development of magnetospheric storms, through collaborations in various global modeling efforts.

DISCUSSION AND CONCLUSIONS

Plate 3 illustrates the need for a higher-dimensionality view of ionospheric plasma in convecting plasma flux tubes, that has become apparent from the TIDE-PSI results. Here, the (periodic) convection cycle is represented along the x-axis, while the altitude profile along a flux tube is represented by the y-axis. The closed cycle convection is taken to begin immediately equatorward of the dayside auroral zone, or cusp/cleft region. Each plasma flux tube arrives at that position after a prior cycle around the prevailing circulation pattern, even if the precise circulation pattern has not been constant in magnitude or topology. Such an approach must take the place of the traditional one-dimensional description of a polar wind flux tube.

Plasma flux tubes circulate repeatedly around the high latitude convection flow pattern, and are repeatedly subjected to sunlight and and darkness, flow shears, associated current sheets, precipitating energetic particles, and turbulence that result from the continuing interaction with the flowing solar wind. Most relevant to plasma outflows is the input of significant electron and ion heating, as well as parallel electric field accelerations in regions of strong field-parallel electrical currents. These effects influence strongly the mass flux of the ionospheric outflows, principally through the addition of O^+ ions to the outflow. Flux tubes also undergo the cycle of elongation and relaxation that accompanies a trip through the magnetotail and plasma sheet.

At higher altitudes, the plasma flux tubes experience other effects including superthermal electron populations originating both in ionosphere (photoelectrons) and in the solar wind (polar rain electrons). These populations may conspire to create standing electrostatic potential structures across parts of the polar cap, that accelerate or decelerate the polar wind and heavy ion outflows. The plasma ions are also subject to centrifugal forcing owing to the interactions of the geoelectric and geomagnetic fields and the accelerations of the plasma convection frame. The result is a convection-driven "flinging" of especially the heavy ions down the tail. As noted earlier, such effects control the degree to which ionospheric plasma is lost to the downstream solar wind, accelerated by neutral sheet effects in the mid-tail, or circulated with little acceleration into the inner magnetosphere, becoming part of the refilling of the plasmasphere. All of these effects must ultimately be included in a complete theory of the terrestrial polar wind.

The increasing evidence that the ionosphere typically and continuously supplies plasma to the plasma sheet, has led to recent efforts to include an ionospheric fluid within global circulation models of the magnetosphere [*Winglee et al.*, 1997, 1998, unpublished manuscript]. This initial effort suggests that the pressure geopause encompasses much of the plasma sheet Earthward of the persistent neutral line, except during northward IMF conditions. That is, the ionosphere dominates the pressure in the active part of the plasma sheet for typical conditions. In view of this significant result, other efforts to include the ionospheric plasma as a dynamic component of the magnetosphere can be anticipated to follow, and are already beginning [*Song et al.*, 1998].

Plate 4 illustrates the destiny of the polar wind outflows as they, to varying degrees, escape down the tail lobes, become trapped in the earthward flow of the central plasma sheet, or are recirculated into the inner magnetosphere through the plasmaspheric trough region. The entire high latitude ionosphere can be thought of as differing from the low latitude ionosphere or plasmasphere mainly as a participant in the boundary layer flows of magnetospheric plasma. Because these flux tubes spend part of their convection cycle open to solar wind entry, the ionospheric outflows will be inhibited where solar wind pressure is signfiicant, for example in the low latitude boundary layer, where outer plasmaspheric or trough plasma mixes with solar plasma. In contrast, those flux tubes which reconnect through the cusp region pass into the high latitude boundary layer that constitutes the supersonic wake of the solar wind. Here there is a correspondingly vanishing solar wind plasma pressure that assures supersonic polar wind outflow.

This schematic view of ionospheric outflow morphology suggests that the ionospheric supply of plasma to the plasma sheet will be significantly augmented (if not displaced) by solar wind plasma as the interplanetary magnetic field rotates to northward, and the high latitude portion of magnetospheric convection shuts down. Conversely, when southward IMF causes the polar lobe flows to dominate magnetospheric convection, the central plasma sheet will be dominantly supplied with ionospheric outflows that have little solar wind content. Global models of the type that are now developing should be a signficant aid in understanding how the geopause extent varies over the more typical cases that are intermediate between these extremes.

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FIGURE CAPTIONS

Figure 1. Velocity distribution in the TIDE energy range, showing combined low energy ionospheric and magnetosheath components, as indicated in the fit parameters (m2 = normalization; m3 = velocity in km/s; m4 = Temp. in eV). [after Chandler et al., 1998].

Plate 1. Characteristics of bulk transport of ionospheric plasma heated by auroral processes. The panels indicate the distribution of such events in location (near 1 R_E altitude), parallel flux, parallel velocity, and mean temperature. [after Giles et al., 1997].

Figure 3. Observations of ~1 R_E polar wind density and velocity versus solar zenith angle, illustrating solar illumination control of polar wind H^+ and O^+ densities (and therefore H^+ flux at relatively constant velocity). [after Su et al., 1998a]

Figure 4. Observations of topside O^+/H^+ plasma flows, showing that O^+ is on average downward moving in the polar cap. [after Su et al., 1998a]

Figure 5. Observed characteristics of the high altitude polar wind, for H^+ (left panels) and O^+ (right panels), in density, velocity, parallel and perpendicular temperatures. [after Su et al., 1998a]

Figure 6. Observations of plasma convection in the high altitude polar wind, showing antisunward convection during a period of generally southward IMF and vice versa during a period of northward IMF [after Elliott et al., 1997].

Plate 2. High altitude polar wind ion energy (upper panel) and spin angle distribution (middle panel) for an event exhibiting strong fluctuations of the parallel polar wind streaming velocity (lower panel).

Figure 8. A categorization of the types of trajectories (projections in the GSM X-Z plane) resulting from initial conditions corresponding to typical polar wind velocities and locations of observation. [Giles et al., 1997].

Plate 3. Schematic of plasma flux tube behavior during repeated high latitude convection cycles, including relevant low altitude and high altitude heating and acceleration processes. Flow streamlines are indicated as fine hairlines. The terminator is illustrated as a dashed line. The x-axis is periodic and wraps back to the origin.

Plate 4. Schematic of ionospheric outflow destiny in the magnetotail, in relation to familiar structures in both the equatorial plane (upper panel) and the noon-midnight meridian (lower panel).

Figure 1. Velocity distribution in the TIDE energy range, showing combined low energy ionospheric and magnetosheath components, as indicated in the fit parameters (m2 = normalization; m3 = velocity in km/s; m4 = Temp. in eV). [after Chandler et al., 1998].

Plate 1. Characteristics of bulk transport of ionospheric plasma heated by auroral processes. The panels indicate the distribution of such events in location (near 1 R_E altitude), parallel flux, parallel velocity, and mean temperature. [after Giles et al., 1997].

Figure 3. Observations of ~1 R_E polar wind density and velocity versus solar zenith angle, illustrating solar illumination control of polar wind H^+ and O^+ densities (and therefore H^+ flux at relatively constant velocity). [after Su et al., 1998a]

Figure 4. Observations of topside O^+/H^+ plasma flows, showing that O^+ is on average downward moving in the polar cap. [after Su et al., 1998a]

Figure 5. Observed characteristics of the high altitude polar wind, for H^+ (left panels) and O^+ (right panels), in density, velocity, parallel and perpendicular temperatures. [after Su et al., 1998a]

Figure 6. Observations of plasma convection in the high altitude polar wind, showing antisunward convection during a period of generally southward IMF and vice versa during a period of northward IMF [after Elliott et al., 1997].

Plate 2. High altitude polar wind ion energy (upper panel) and spin angle distribution (middle panel) for an event exhibiting strong fluctuations of the parallel polar wind streaming velocity (lower panel).

Figure 8. A categorization of the types of trajectories (projections in the GSM X-Z plane) resulting from initial conditions corresponding to typical polar wind velocities and locations of observation. [Giles et al., 1997].

Plate 3. Schematic of plasma flux tube behavior during repeated high latitude convection cycles, including relevant low altitude and high altitude heating and acceleration processes. Flow streamlines are indicated as fine hairlines. The terminator is illustrated as a dashed line. The x-axis is periodic and wraps back to the origin.

Plate 4. Schematic of ionospheric outflow destiny in the magnetotail, in relation to familiar structures in both the equatorial plane (upper panel) and the noon-midnight meridian (lower panel).

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